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RESEARCH MEMORANDUM

REVIEW OF PROBLEMS OF CONSERVATION OF STRATEGIC MATERIALS FOR TURBINE ENGINES

By Materials Research Staff

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
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RESEARCH MEMORANDUM

REVIEW OF PROBLEMS OF CONSERVATION OF STRATEGIC MATERIALS FOR TURBINE ENGINES*

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INTRODUCTION

Most current work on the conservation of strategic materials for turbine engines applies specifically to the turbine blade and the turbine disk. Because these components operate under the severest conditions of stress and temperature, they constitute the most difficult components from which to remove strategic elements. Hence, a major portion of the materials research has been concerned with these components. Other portions of the engine, however, also contain strategic material; in most cases, the strategic-material content of the remainder of the engine is far greater than that of the disk and the blades. This paper, therefore, discusses the strategic-material problems of the engine as a whole.

The material problems of the engine may be summarized briefly as follows: The elements that are normally included in alloys to impart high-temperature strength and resistance to corrosion are in short supply. The most rapid progress in the early stages of development of a given engine can be made by using the best available materials. During normal peacetime conditions, when engine production is quite low, it may also be acceptable to make engines of the best available materials. When production requirements become so great, however, that there is not enough material available to meet demands, methods must be sought to minimize the strategic-alloy content of every engine. Production requirements at the present time are already very high and they are increasing. It is, therefore, particularly urgent that problems of material availability be evaluated and methods be sought to reduce engine strategic-alloy content.

This paper presents several possible approaches to the material-conservation problem - the advantages and disadvantages, and the relative

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*This Research Memorandum contains essentially the same information as presented in a speech at the NACA Turbine Materials and Cooling Conference (Cleveland, O.) March 15, 1951.

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gains that might result from one, or combination of a number, of these approaches. For the sake of simplicity, discussion is limited to considerations of raw-material availability only. Other factors of importance such as those of cost, producibility, and manufacturing capacity, which must inevitably be considered in making final decisions of the optimum approach, are considered outside the scope of this paper.

CRITICAL MATERIALS

In order to gain an idea of the scarcity picture for each of the important elements, refer to figure 1. This figure presents three bars for each element; the height of the first bar represents the estimated availability of the element based on stock piles and production capacity of the North American continent only. The availability bars for the various elements are all drawn the same height, although the actual amounts available are far different for each of the elements. There is, for example, many times as much cobalt available as columbium. The elements are listed in order of increasing availability, from left to right.

The height of the second bar for each element represents the quantity of that element, relative to the availability bar, required to maintain an arbitrary annual production rate. The rate considered is low in comparison with the peak annual engine-production rate attained during World War II of 267,000 engines. The third bar for each element represents the requirements for that element for essential uses other than engine production. Because the estimates involved in figure 1 are dependent on so many unknown and changing factors, the bars are shown broken at the top. They do indicate, however, relative magnitudes that are sufficiently accurate for the present dicussion.

The worst case is seen to exist for columbium. Here, the quantity required for turbine engines alone far exceeds the quantity available. Even neglecting other essential uses, there would not be enough columbium available to meet aircraft turbine-engine requirements. It is, therefore, imperative that means be found to eliminate, or at least drastically reduce, the use of this element.

Cobalt is the next most critical element. Here, the requirements for turbine engines again exceeds the total supply, even disregarding other uses, but not by so great a factor as columbium. Elimination of its use wherever possible is, however, necessary.

Tungsten is critical for a somewhat different reason. Turbine-engine requirements are not nearly as great as the available supply. The requirements for other essential uses are, however, larger than the supply. It is therefore desirable to restrict its use wherever possible in order to insure that its availability does not become a limiting factor in engine production.

Chromium metal, as distinguished from ferro-chromium, shows the same general picture as tungsten in that supply is low in comparison with total requirements, and high in comparison with turbine-engine requirements. More encouraging, however, is the fact that there are considerable quantities of chromite ore available from which chromium metal (in preference to ferro-chromium) could potentially be produced, providing that production facilities could be greatly enlarged.

Other elements that may limit the production of turbine engines are also indicated in figure 1. These are molybdenum, nickel, and chromium in the form of ferro-chromium. While these elements are generally available in large quantities, the supplies are, of course, finite, and depending on changing requirements both for turbine engines and for other uses, any one may become the restricting element. For these materials, present turbine-engine requirements are low in comparison with other uses and current metal-production rates are high because of the greatly developed uses for other purposes.

LOCATION OF STRATEGIC ELEMENTS IN ENGINE

Consider next the locations at which these elements are used in a typical turbine engine. Figure 2, which depicts the locations of columbium, presents a schematic sketch of an axial-flow turbine engine, with afterburner, representing a composite of a number of production engines, and the typical operating temperatures that exist in the various parts. The possible places where columbium is used are indicated by the heavily hatches areas. In any one engine, columbium would not be in all of these components. Most of the columbium used is found as type-347 stainless steel in both the hot and cold ends of the engine. Lesser amounts are used in blades, in those engines using such alloys as S-816 for blades. A very small amount must be considered for the disks, due to some use of 19-9 DL alloy for this purpose. Again, it might be found in Inconel-X combustion-chamber liners or in afterburners of N-155 or Inconel-X alloys. The most striking feature about figure 2 is that a major percentage of the columbium used is in parts operating at fairly low temperatures.

The locations of cobalt are shown in figure 3. This element will be found in a number of alloys in current use as listed in the chart. All the applications of this element are in hot parts of the engine.

Tungsten and chromium metal required for alloys are used in the engine as indicated in figures 4 and 5, respectively. These elements are used in stator or rotor blades, in the disk, and in afterburners as the various alloys listed.

Chromium, in ferro-chromium, and nickel are used throughout the engine, the amounts required being large in comparison to the metals previously discussed. While reductions in the amounts of nickel or of chromium required for any one component would be small in comparison to the over-all requirements for engines, the savings to be gained by such conservation measures are none the less important, due to the generally short supply of these materials.

APPROACHES TO REDUCTION OF STRATEGIC CONTENT

Several possible approaches to the strategic-material problem exist. One of these consists in substitution of less strategic materials, having reasonably equivalent properties, for highly strategic materials. One such substitution possible is that of type-321 stainless steel for type-347 stainless steel. As stated previously, most of the columbium used in an engine is contained in type-347 steel; hence, the substitution of type-321 would greatly reduce the need for columbium. Type-321 is equivalent, in most properties, to type-347. The substitution path is being actively followed by engine manufacturers and many such substitutions have already been made in production engines.

Another possible substitution is that of columbium-plus-tantalum alloys for columbium, in stainless steels and in such alloys as S-816. If such substitutions are successful, the effect would be equivalent to increasing the supply of columbium 30 to 50 percent.

Another example of this approach is the substitution of nickel-base alloys for cobalt-base alloys, particularly where the cobalt-base alloys also contain columbium. On the basis of American and British experience, it may be possible to produce high-nickel alloys that are essentially comparable in properties to current cobalt-base alloys. Nimonic 90, an alloy upon which information has only recently been released, is an example of these high-nickel alloys. Turbine blades of Refractaloy 26, an alloy containing 37 percent nickel, have performed well in engine operation.

The principal advantage of substituting nickel-base alloys for cobalt-base alloys lies in the fact that large quantities of nickel are available on the North American continent. Furthermore, turbine-engine requirements for nickel are, in general, small compared to the demand for other uses. In order to obtain adequate performance with nickel-base alloys, however, it may be necessary to use those containing some cobalt. For example, both Nimonic 90 and Refractaloy 26 contain approximately 20-percent cobalt. The demand for cobalt would be less with use of these alloys, however, than with use of cobalt-base alloys. A word of caution is needed here. Increase in use of nickel-base alloys will depend to a great extent on such factors as ability to produce the alloys in the large amounts and in the high quality required for aircraft use. Present production limitations severely restrict the extent to which utilization of nickel can be increased immediately.

The substitutional possibilities indicated above are, of course, only typical of this main classification. Other possibilities are being actively pursued by the various manufacturers.

A second approach to the problem of reducing strategic-material use consists of the direct substitution of alloys of lower strategic-material content for those currently in use for components that may not require the high properties of the materials now being used. For example, in some cases replacement of type-347 stainless steel need not be with type-321, which reduces only columbium content, but may be as drastic as the substitution of ordinary 1010 steel. Such a substitution would save nickel and chromium also. Such components as outer combustion housings, which operate at essentially low levels of stress and temperature, fall into this category. In some cases, protective coatings may be required to prevent corrosion. Another example is the substitution of low-alloy steels for stainless steels in bearing housings. There are many other similar examples throughout the engine.

A somewhat different approach to the problem of materials conservation consists of prolonging the life of engine parts so that total engine requirements for a specific amount of engine operation are reduced. If the time to first failure of existing turbine blades can be substantially increased by improving metallurgical processing, the number of spare parts required is reduced, as is the number of stand-by engines. The effects are cumulative and may add up to great savings, even if the use of current materials is continued. Similar gains, but perhaps of smaller magnitude, may be possible by the exercise of closer control of existing metallurgical procedures.

Another approach is the possibility of reducing alloy-strength requirements by reducing metal operating temperatures. One way of achieving this is use of cooling. For example, reducing blade temperature by cooling makes possible the use of alloys of lower strategic content. The potential gains from this type of approach are great. The disadvantages must, however, be considered: (1) There will be some loss in performance, and (2) some time must be allowed for the development and service testing of effective types of blade-cooling systems. Also, experience must be gained in manufacturing methods.

Wheel cooling can more readily be put into application than blade cooling, especially on wheels that already are cooled at their centers for protection of bearings. Changing to cooled wheels would not only reduce strategic-material content, but, if carried far enough, would improve the potential production rate because the materials that could be used are easier to fabricate than those currently used.

Reducing gas temperature is another means of reducing alloy requirements, but some penalty must be paid in reduction of thrust. It is significant, however, that the reduction in temperature necessary to bring into potential use materials of much reduced strategic metal content, are, in some cases, quite low. For example, alloys such as 16-25-6 and Nimonic 80A cannot be considered equivalent to S-816 on the basis of stress-rupture properties at current operating temperatures. According to stress-rupture data, these alloys should, however, if operated at temperatures 100° to 150° F below current temperatures, have the same life as S-816 at current operating temperatures. The reduction of gas temperature by 100° F to 150° F would necessitate accepting a reduction in thrust of about 7 to 10 percent.

Another approach consists of development of new materials having lower strategic-material content but possessing properties at least equivalent to those in current use. Progress in this direction in the use of ceramics, ceramals, and intermetallics is being made. Ceramals and intermetallics offer future possibilities, particularly for expendible missile engines, but problems of low ductility, in particular the fastening problem, must be solved before these materials can be considered for use in current engines. Ceramics, while not especially promising for turbine rotor blades, may be useful for other components such as nozzle vanes or for protective coatings of various types to prevent corrosion.

Development of useful molybdenum alloys is a possibility. Molybdenum has outstanding high-temperature properties, which will probably be further improved by suitable alloying. It possesses the disadvantage of very poor oxidation resistance, however, and its use will involve the development of suitable protective coatings. Some progress has already been made in this field.

Because the raw materials for production of titanium-base alloys are in large supply on this continent and because such alloys have attractive strength and corrosion-resistance properties, developments in this field offer considerable promise. For example, a titanium alloy would have advantages as a compressor-blade material and would replace a

13-percent-chromium ferrous alloy currently used. Some tests of titanium alloys already performed by the engine manufacturers for such parts as forged compressor blades or disks are promising. The future feasibility of such substitutions in large numbers of engines centers around the development of adequate production capacity and solution of the inherent production problems.

Improvement in component design is a promising method for reducing the strategic-material content of engines. Reduction of weight of turbine disks is one method; a second is improvement of design to minimize vibrational fatigue. Unpublished data indicate that alloys will give a life in the engine as great as one could expect them to have on the basis of stress-rupture tests, provided that fatigue does not enter to cause premature failure. Many of the failures that have been encountered in blades have been of the fatigue type; hence, improvements in blade and engine design that will either reduce vibrational exciting forces, make the blade more resistant to existing exciting forces, or introduce damping to prevent build-up of vibratory stress will reduce the number of failures.

The final means of material conservation to be considered here has to do with improved manufacturing and scrap-handling procedures. The rough weight of a part may be as much as five times the finished weight. This difference means that, for some parts, as much as 80 percent of the material procured is not used in the engine. The savings to be made in this area of production are of the first order of magnitude. There will always be scrap produced in the manufacturing processes; it is essential that every effort be made to segregate the scrap and re-melt it for use only in the production of highly alloyed metals. As a result, the alloy producer could use a higher ratio of scrap to virgin material.

It should be pointed out here that it will be necessary to investigate potential material substitutions in actual engines and to obtain service test data on their performance. Very few material changes will be put into general practice, regardless of laboratory indications, until a type test has been successfully completed.

ILLUSTRATIVE EXAMPLES OF REDUCTION OF STRATEGIC MATERIALS

The foregoing discussion has enumerated various approaches that could, either individually or collectively, assist in relieving the strategic-materials problem. This section presents the results of several studies that were made to provide a better understanding of the problem and to gain some insight into the extent to which several changes, selected from those previously enumerated, would relieve this problem. In order to make the discussion definite the engine considered is a hypothetical composite of a number of engines that has components in accord with manufacturers' material specifications of some six months ago. As indicated previously, material-availability figures are estimates made several months ago of stockpile and production capacity of the North American continent. Because availability figures and material specifications are constantly changing, the use of more recent figures would alter the precise quantitative results, but the general trends and the conclusions to be drawn from such a study will remain essentially unchanged.

The results of the first study are shown in figure 6. In Section I is plotted the number of present engines, on a relative basis, that could be produced from available materials if production were limited only by each of the various strategic elements taken successively. It is seen that columbium is indicated as the current limiting element. If the number of producible engines as restricted by columbium supply is taken as unity, the number of engines that could be built if only cobalt supply limited production would be $3\frac{1}{2}$. Limitation by chromium supply would be 4, by tungsten about 5, etc. It can be seen that a much larger number of engines could be built if the limitation was in ferro-chromium, nickel, or molybdenum. If type-321 stainless steel were substituted for all the type-347 stainless steel used in the hypothetical engine, it would, as previously indicated, reduce the columbium requirements. The number of engines that could then be built if each one of the elements were independently the restricted one, is shown in Section II. It may be noted that the relative number of available engines has increased to about 4, and that chromium metal has become the limiting element; columbium, cobalt, and tungsten are, however, very close to limiting. In order to change the picture appreciably now, a substitution must be made that will affect each of the first four elements shown.

The type of substitution assumed, and the results effected, are shown in Section III. Here it has been assumed that all cobalt in the engine other than that contained in the blades has been eliminated. This assumption is not unreasonable. The blade alloy that has been assumed has the following characteristics: It has a high nickel content; columbium and tungsten have been eliminated, or drastically reduced; cobalt has been reduced to about 20 percent; and chromium metal has been replaced by ferro-chromium (that is, the alloy is assumed to contain a sufficient amount of iron to allow the ferro-chromium substitution). The limiting element is now nickel and the maximum number of engines that can be made is about 10 times the number permitted by the current columbium limitation.

A logical further step at this point would be the reduction of nickel by the introduction of disk-rim cooling and construction of the disk from a low-nickel alloy instead of the current high-nickel alloys. It is seen, however, that cobalt would soon again become the limiting element. Substitution of a ferritic wheel material would, however, be very desirable not only because it would reduce the amount of nickel, but because it would simplify manufacturing procedures.

Another approach to the problem is shown in figure 7. The first two sections are the same as those of figure 6. Section III assumes that blade temperature has been reduced about 100° to 150° F by reducing inlet-gas-temperature, and that an iron-base alloy high in chromium, nickel, and molybdenum has been used as the blade material. It may be seen that while the columbium, cobalt, chromium, and tungsten limitations have been reduced, molybdenum has become the limiting element. This limitation is imposed because molybdenum has been added to the blades, and because the disk also contains an appreciable amount of molybdenum.

In order to reduce the molybdenum requirement, a substitution must be made in the disk. Since the gas temperature has been assumed reduced by 100° to 150° F, it might be possible to substitute a twelve-percent-chromium ferritic disk with a small amount of rim cooling, or even directly without any cooling.

The same result could be achieved by cooling the blade about 100° to 150° F; the disk being cooled incidentally to blade cooling. The results are shown in Section III of figure 8. Again, nickel is the limiting element and about 13 times as many engines can be made as when columbium supply limited production. Further large increases in producibility could be achieved by further cooling; only, however, if nickel is removed from other portions of the engine, as well as from the blades. The nickel limitation exists because nickel is present in such large quantities in engine components other than the blades that simply removing it from the blade does not appreciably alter the total amount used in the engine. However, assuming that nickel is reduced in other portions of the engine, temperature reductions greater than 150° F produced by blade cooling would show up to advantage.

CONCLUDING REMARKS

The foregoing discussion has shown the need for reducing the use of columbium and, to a slightly lesser extent, the use of cobalt, in order that supplies of these elements may not limit engine production. General methods by which this can be accomplished have been outlined.

Any specific solution will probably involve combinations of the general possibilities suggested, depending on individual engine designs and requirements. Substantial increases in engine producibility are entirely feasible and much actual progress is being made.

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Accomplishments of these changes will not be easy. Much research and development is necessary, particularly in the field of production problems. The capacity for manufacturing larger quantities of alloys than heretofore possible must be attained.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
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[redacted]

Figure 1.- SCARCITY OF ELEMENTS IN TURBINE ENGINES

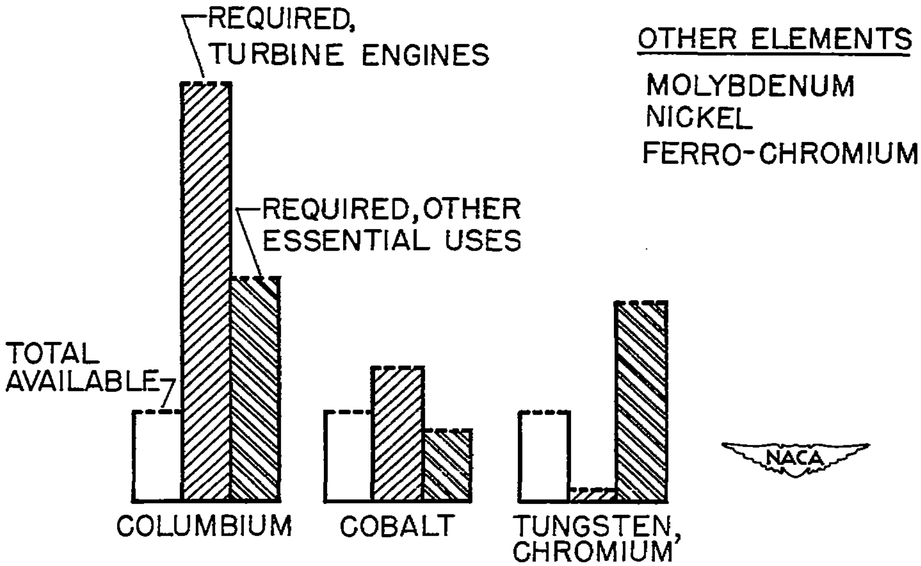
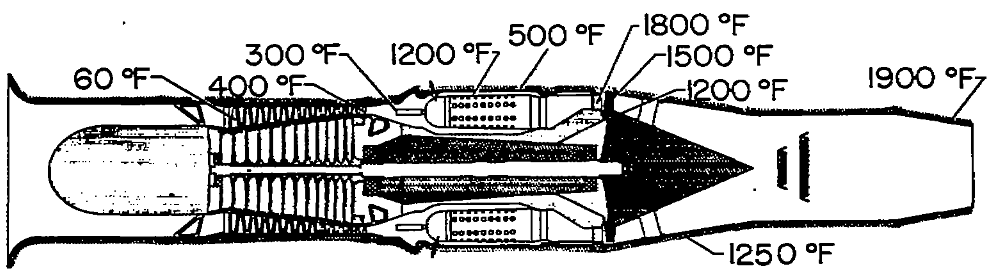


Figure 2.- DISTRIBUTION OF COLUMBIUM IN ENGINE



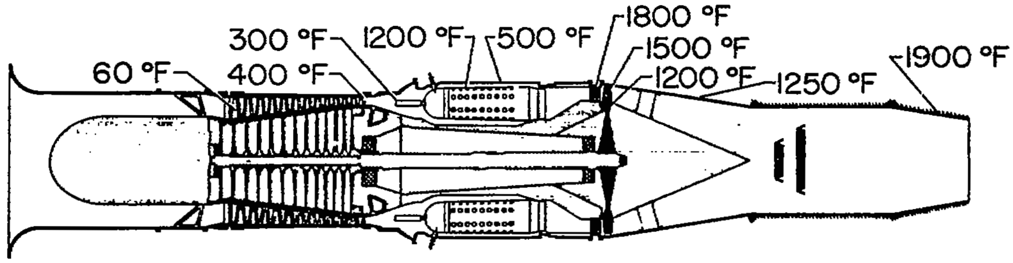
COMPONENT	ALLOY
SHEET METAL (HOT)	347
SHEET METAL (COLD)	347
FORGINGS & CASTINGS	347
TURBINE BLADES	S 816 INCONEL X
DISK	19-9 DL
AFTERBURNER	N 155 INCONEL X

COLUMBIUM

[redacted]

[redacted]

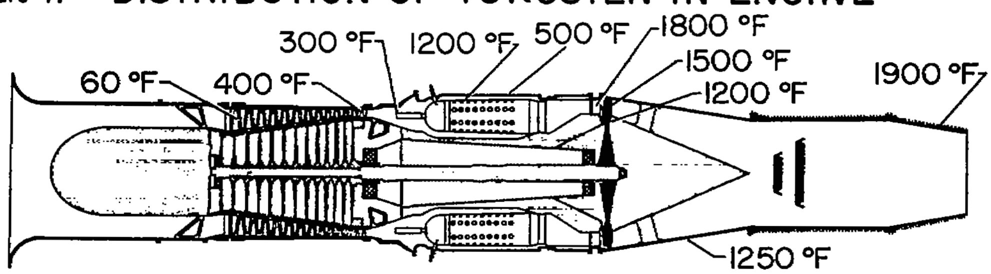
Figure 3.- DISTRIBUTION OF COBALT IN ENGINE



COMPONENT	ALLOY
TURBINE BLADES	STELLITE 21
	NIMONIC 90
	S 816
	L 251
	STELLITE 23
	STELLITE 31
NOZZLE VANES	STELLITE 21
	REFRACTALOY 80
DISK	G 18 B
AFTERBURNER	L 605
	N 155

COBALT

Figure 4.- DISTRIBUTION OF TUNGSTEN IN ENGINE



COMPONENT	ALLOY
BLADES	STELLITE 23
	STELLITE 31
	L 251
	REFRACTALOY 80
	S 816
DISK	19-9 DL
AFTERBURNER	L 605
	N 155

TUNGSTEN

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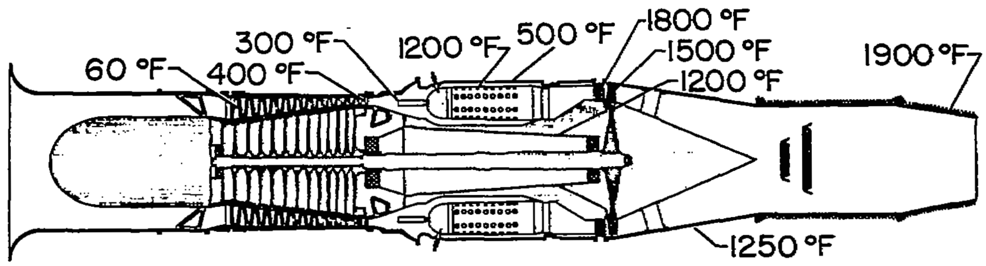
Figure 5.-DISTRIBUTION OF CHROMIUM IN ENGINE

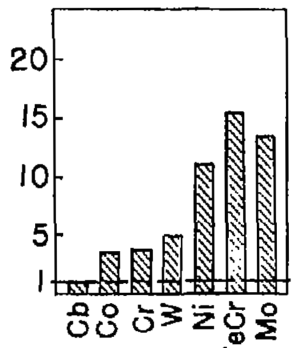


COMPONENT	ALLOY
TURBINE BLADES---	NIMONIC 80
	NIMONIC 90
	L 251
	S 816
	STELLITE 31
	STELLITE 23
AFTERBURNER-----	NIMONIC 75
	L 605
NOZZLE VANES-----	STELLITE 21

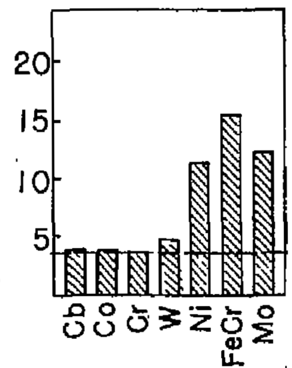
CHROMIUM

[redacted]

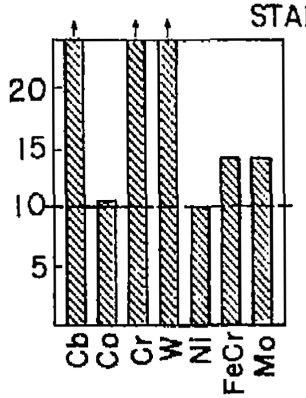
Figure 6. - INCREASED ENGINE PRODUCIBILITY



I PRESENT ENGINE

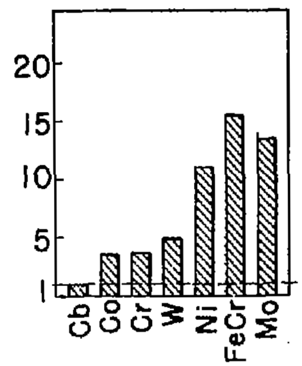


II Ti FOR Cb IN STAINLESS STEEL

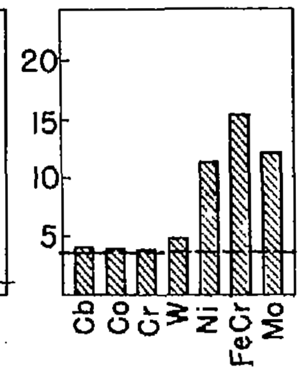


III IN TURBINE BLADE
1. REDUCE COBALT
2. ELIMINATE COLUMBIUM
3. FERRO-CHROME FOR CHROMIUM
REMOVE COBALT IN REST OF ENGINE

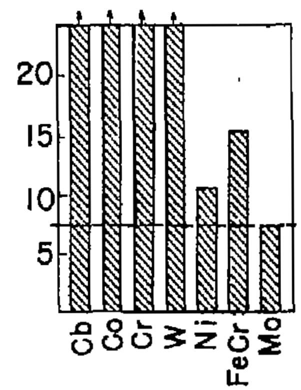
Figure 7. - INCREASED ENGINE PRODUCIBILITY



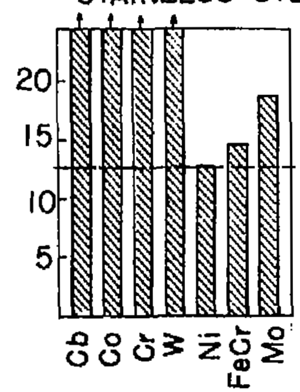
I PRESENT ENGINE



II Ti FOR Cb IN STAINLESS STEEL



III REDUCE INLET-GAS TEMP 100 TO 150 °F



IV DISK COOLED

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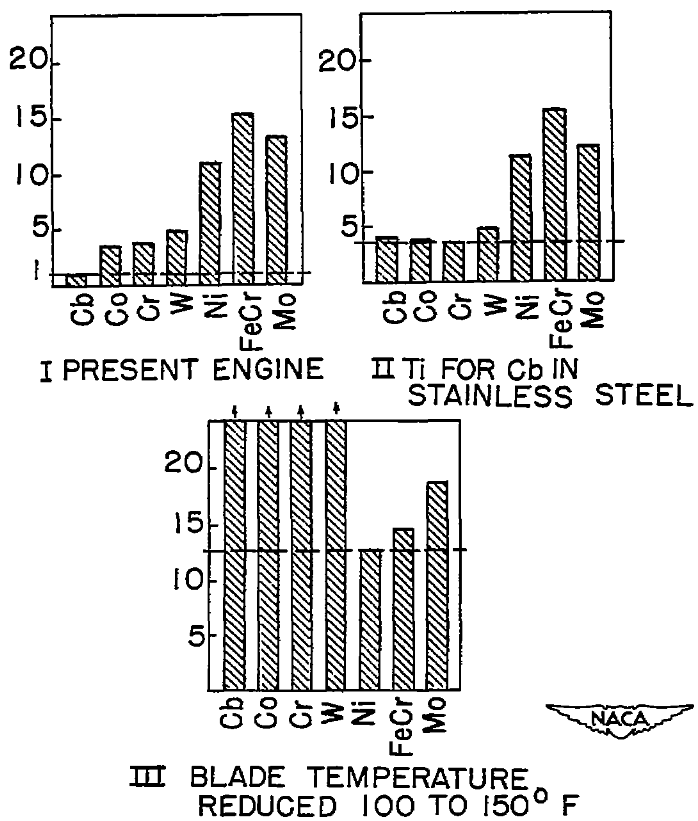
Figure 8.- INCREASED ENGINE PRODUCIBILITY



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